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# Old Know-How in Helix TWT Development in the USSR

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**Abstract.** In the USSR, the first traveling wave tube (TWT) was developed in 1946. This was followed by the invention of the first backward-wave oscillator (BWO) and other important achievements, which could characterize a strong competition existed between American and Soviet scientists and engineers. In the present paper, some of the achievements of the first soviet TWT team, headed by L. N. Loshakov, are discussed. Among those achievements are invention of the two-anode gun for a low-noise TWT, development of the first three-octave TWT, and development of the helix TWT linear theory. In this paper, also such issues as formation of the rotating electron beams, suppression of reflected waves, multi-stage TWTs, amplification without synchronizing electron and wave velocities, utilization of beryllium oxide and quartz rods in one RF set, dispersion control by application of metal support rods, and many other engineering solutions are presented.

## INTRODUCTION

It is known that the first traveling wave tube (TWT) was invented in 1944 by R. Kompfner [1], and soon after, TWT theory was developed by J. Pierce [2]. Less known is the fact that USSR scientists and engineers started TWT development only two years later, sometimes overtaking and passing their American colleagues. By the end of 1946, the year of the first published papers on TWT, a team of young militaries headed by L. N. Loshakov demonstrated the first performance of Soviet TWT. Before being mobilized by the Soviet military forces, L. N. Loshakov was working at Moscow State University. There, he accumulated a rich experience in the physics of microwave tubes. His Ph.D. was done in klystrons. Studying the interaction of a linear electron beam with an electromagnetic field in klystron resonators, he had found the effect of amplification of an electron beam modulation in the circuits with distributed parameters.

## FIRST STEPS

Initial investigations done by Loshakov's team were concentrated on better understanding of an electron beam interaction with a slow wave. It resulted in the development of the low-noise TWT with two-anode electron gun and discovering of the backward oscillations. In 1948 were created first BWO with output power 300-500 mW in the 3-5 cm band. In 1951 the 8 mm BWO was already manufactured for

military equipment. Also, in this short period of time (1946-1949), Loshakov created a basics of the helix TWT linear theory [3]. This theory was practically completed by Loshakov and his students to the end of the 1950's. Among the results obtained were the following: correct solution of the TWT dispersion equation, optimization of attenuator's parameters, valuation of supporting rods influence, etc.

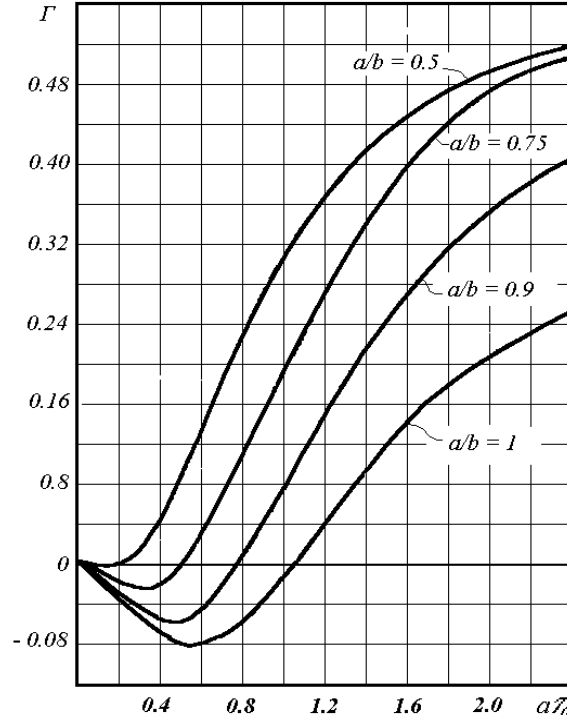
Further works done by Loshakov's division in the 1950's-1970's has been focused on helix TWTs, as well as on bifilar and comb BWOs. The main attention was paid to the following issues:

- increase in the electron beam density,
- new methods of electron beam focusing, including the centrifugal electrostatic focusing,
- increase in gain and output power,
- frequency bandwidth widening.

The main results in the theory were published in academic journals and later were summarized in the monograph on the helix TWT linear theory [4].

## INVESTIGATIONS

The increase in the gain and output power required a detailed investigation of the space charge and attenuator influence on the gain and efficiency. This required solving the TWT equation in the case of relatively large space charge and large loss that was not a simple task.



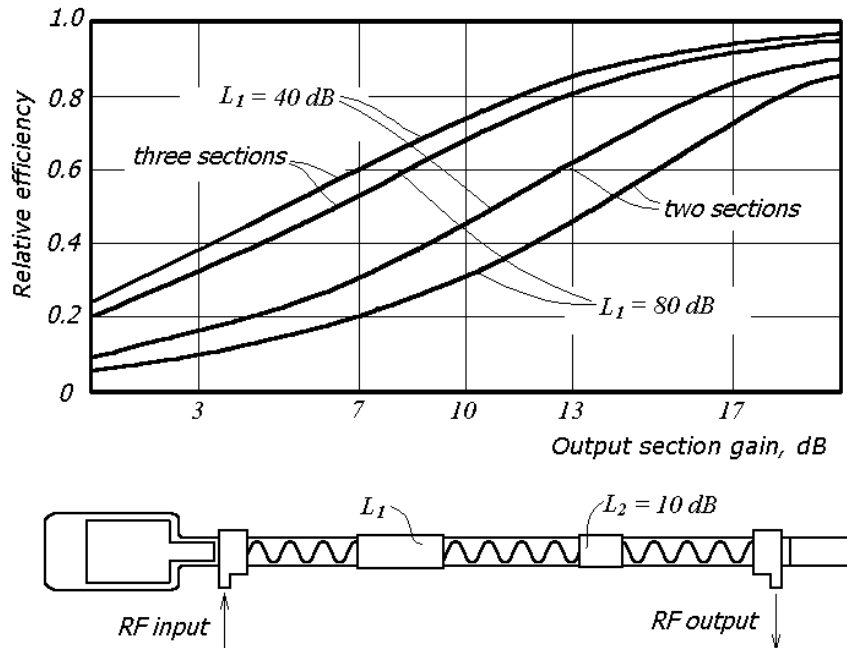
**FIGURE 1.** Depression factor  $\Gamma$  dependence upon a beam parameter  $\alpha\tau_0$  for different ratios of the beam to a helix radiuses  $a/b$ .

## Space Charge

The main obstacle in the solution of the TWT equation was the correct calculation of the so called depression factor  $\Gamma$  which takes into account the space charge influence on the gain, efficiency, and the optimum ratio of the beam and amplified wave velocities. Defining correctly enough the interaction factor, all publications before 1957 exposed different expressions for the depression factor. In 1956, author of this paper showed that the depression factor is a passive part of the plasma frequency reduction factor and that a much higher accuracy than in the case of the interaction factor is required for its calculation. The unexpected fact was the negative value of  $\Gamma$  at relatively small frequency (Fig. 1). From practical point of view, this means that the beam modulation can grow without its synchronism with the wave. According to the analysis, one can create a very broadband “inductive” TWT using the negative depression factor [5]. As was shown later by V. A. Solntsev, the correct value of  $\Gamma$  is very important for non-linear analysis.

## Attenuator

In the first version of TWT a nichrome helix was used to suppress the self-oscillation caused by a signal reflection from the input and output of the TWT. Such TWT had not only small gain but also very small efficiency. The analysis done later in 50's showed that a relatively small decrease in the gain caused by the distributed



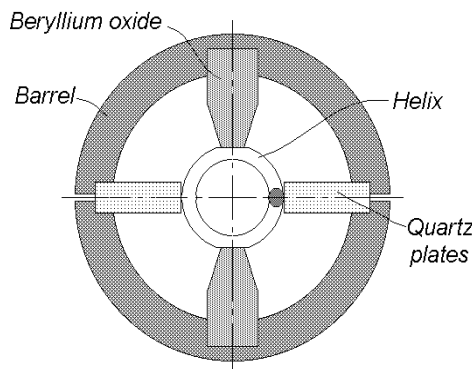
**FIGURE 2.** Relative efficiency dependence on the output section gain for two- and three-section TWTs.

attenuation ( $1/3$  for the small space charge) is followed by the very high decrease in an electronic efficiency. It followed also from this analysis that the attenuator should be positioned in the middle of the slow-wave structure (SWS) while everybody considered that it should be placed further from its end. The theoretical analysis and experiments also showed that in the real structures the growing wave doesn't disappear in the attenuator. After transformation at the attenuator's input it continues to grow dissipating its energy in the attenuator, the loss being proportional to the "cold" value of attenuation  $L$  [6].

Further analysis showed that the maximum gain and better efficiency require two attenuators, the second one having a relatively small loss (Fig. 2).

## Helix Support Techniques

A high level of energy dissipation in the attenuator and the heat caused by the interception of electrons at the end of the helix required replacing the quartz supports, used in the first TWTs, by rods with a good heat conductance. The beryllium oxide ceramic gave the best results, but its application required a new design of the SWS block.



**FIGURE 3.** RF-block with beryllium oxide and quartz supporting rods.

First, the ceramic application increased the load decreasing the gain and efficiency. Second, as it followed from calculations and was confirmed by measurements, application of materials with a high thermal conductivity did not solve the problem. The main thermal resistance is between helix and support rods. We discovered this effect a decade earlier than Scott and Cascone published results of their measurements [7]. For the first time, we used beryllium oxide supports in a 2 Cm TWT. The extra loading problem was solved by the simultaneous application of quartz and beryllium oxide rods in one block (Fig. 3). The problem of thermal contacts was solved by an

increase in interface and by using a hot insertion technique. The small plane areas were machined along diametrically opposed generics of the helix. The oxide beryllium rods with plane edges were pressed to said plane areas. The helix was wound on a 2 mm rod from a 0.3 mm molybdenum wire. The results were fantastic. Designed as 100 W TWT, it provided 200W with 30 dB gain.

## Dispersion

Widening the helix TWT bandwidth was not a simple problem as it could be considered now. First, helix TWTs already had the relatively wide bandwidth. Second, it was not clear what exactly causes the dispersion. This may be illustrated by the erroneous explanation of the helix dispersion given in the well-known Gilmour's monograph [8].

In the case of a helix in free space, the main part of its equivalent specific inductance  $L$  and equivalent capacitance  $C_0$  per unit length are [9]

$$L = \frac{\mu_0}{2\pi} I_1(b\tau) K_1(b\tau) \tan^2 \Phi, \quad C_0 = \frac{\epsilon_0 2\pi}{I_0(b\tau) K_0(b\tau)}, \quad (1)$$

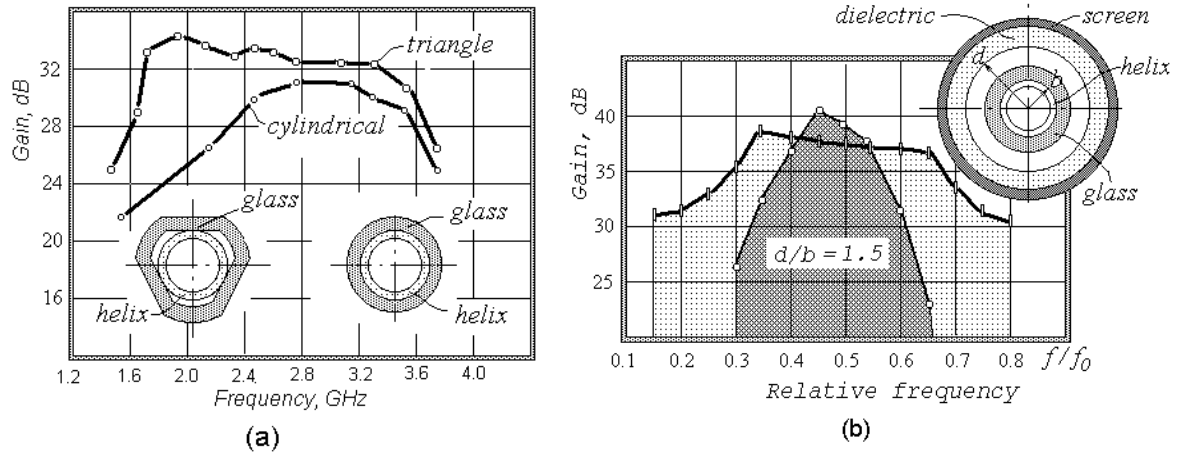
where  $\Phi$  is the angle between winds and longitudinal axes,  $b$  is the helix radius,  $\tau$  is a transverse constant related to phase constant  $\beta$  and wave number  $k$  by the relation

$$\tau^2 = \beta^2 + k^2, \quad k = \omega \sqrt{\epsilon_0 \mu_0}, \quad (3)$$

$\omega$  is an angular frequency,  $\epsilon_0, \mu_0$  are permittivity and permeability of vacuum.

One can see from above formulas that the frequency decrease is followed by the increase in inductance and by the much larger decrease in capacitance that causes dispersion. An additional capacitance that increases with frequency decreasing can help in this case.

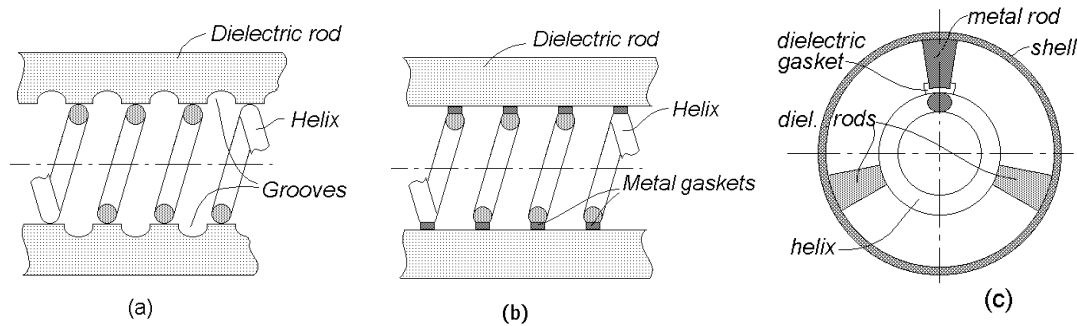
The first ideas and practical results in the solution of the dispersion problem came in the end of 50's when we worked with the new TWTs using the electrostatic centrifugal focusing. Absence of an external focusing system allowed the creation of shells from different materials and with different configuration. When we had begun the work at broadband TWT, it was supposed that dielectric, surrounding the helix, draws in an electric field. Being true for fast electromagnetic waves, it is not so for slow waves. If there is a gap between a SWS and support rods, the electric field is partially reflected by the rods. This effect can be used for a dispersion control. In the case of a needle TWT, a triangulated glass tube broadened a frequency band to one octave (Fig. 4a). An installation of an additional dielectric tube outside a needle TWT (Fig. 4b) resulted in practically constant dispersion and the three-octave bandwidth.



**FIGURE 4.** Dispersion characteristic correction by triangle tube configuration (a) and by a dielectric tube application (b).

In the case of supporting rods, small grooves (Fig. 5a) or metal gaskets between the winds and rods (Fig. 5b) also decrease the helix dispersion.

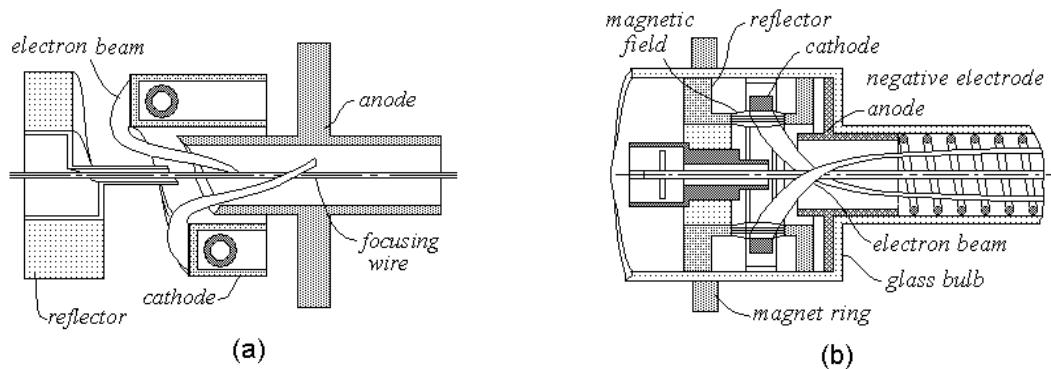
As it follows from the analysis of a helically conducting cylinder in a dielectric tube, the maximum influence on the dispersion may be achieved by an increase in permittivity. It follows from this that a longitudinally conducting cylinder may be used for the helix dispersion control. It took some years and a special analysis to understand that a metal cylinder with longitudinal ribs can replace a longitudinally conducting shield. Although the first measurements with four ribs in a metal cylinder were done in 1964, results of the measurements and calculations were published much later [10]. Despite of positive results, their practical realization was postponed to the end of 60's when we offered the most successful solution based on combined metal-ceramic supports (Fig. 5c). One or some copper rods support a helix through dielectric gaskets. In this design we killed two birds by one stone: decreased dispersion and increased cooling. Later, this design was used in Industry for high power TWTs.



**FIGURE 5.** Grooves in supporting rods (a) and metal gaskets between supporting rods and a helix (b). Combined, metal and ceramic supporting rods (c).

## Electrostatic Focusing

In 50's, when magnetic periodic systems were in childish condition, periodic electrostatic focusing (PEF) and centrifugal electrostatic focusing (CEF) promised to be right solution for middle power TWTs. Nevertheless, as it became apparent in 60's, PEF couldn't be used for TWT: a high focusing voltage caused breakdown between winds, existence of two helices caused backward oscillations. Meanwhile, bifilar helix BWO with PEF was created in NII-160 (later known as "Istok").



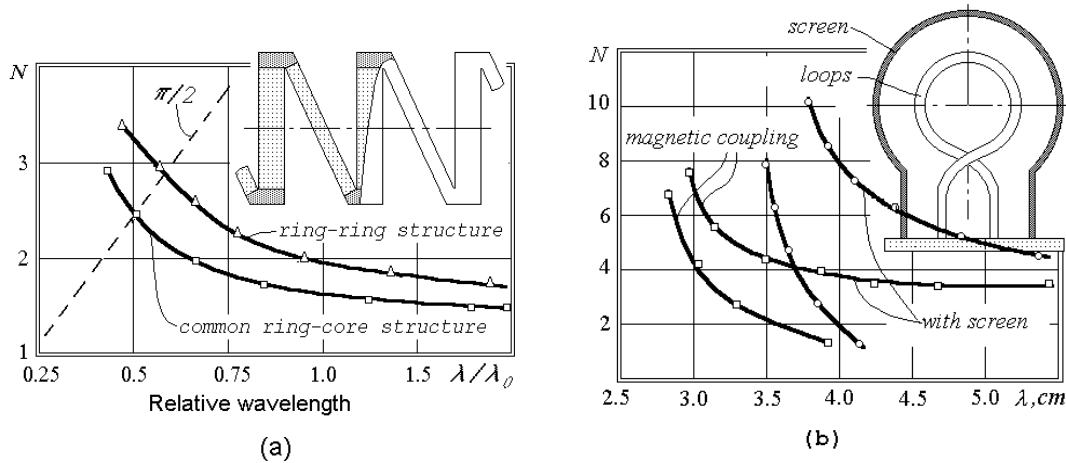
**FIGURE 6.** Chernov's gun with spiral electrodes (a) and author's gun with magnetic field (b).

In 1948, Harris, American Scientist, described the CEF, which could be realized for hollow beams of large diameter. In the beginning of 50s, Z. S. Chernov from Radio-Electronics Institute of the USSR Academy of Sciences created a gun with spiral electrodes. He used this gun for a 10-cm helix TWT with CEF, which he named “spiratron”. The author of this paper had been assigned to develop such TWT for airborne radar.

At that time, many teams in the USSR and some in the USA unsuccessfully worked on the creation of the tubes with CEF. The main trouble was a very poor beam transport (approximately 80 %) that caused a very short lifetime. Besides, self-oscillation caused by the feedback through the focusing wire (the positive electrode of the focusing system which negative electrode is a helix) didn’t allow operating with a gain exceeding 20...25 dB. Chernov’s gun had very complex configuration (Fig. 6a) and was difficult in manufacturing. Very soon it became apparent that it was not possible to create a spiratron for the military application. The problem was solved occasionally. It was discovered that a small magnet near the gun could increase the beam transportation. The simplest solution was a gun without the spiral configuration of the electrodes (Fig. 6b). A magnet ring outside the glass bulb twisted the electron beam and improved transport to 90-98 %. Also, the beam diameter increased that, in its turn, increased the gain and output power approximately ten times.

The increased gain required suppressing the feedback caused by the TEM wave excited near the focusing wire. Installation of rings made from a standard microwave absorbing magneto-dielectric solved this problem completely. Besides, the magneto-dielectric rings installation caused a positive “side effect” similar to above-mentioned correction of dispersion by the dielectric tube.

Later, we offered a combined centrifugal-periodic electrostatic focusing that allowed increasing of the electron beam current and output power [11]. The semiconductors’ revolution in the end of 1960’s stopped further works on the cefotrons development.



**FIGURE 7.** Deceleration  $N$  dependence on the relative wavelength,  $\lambda_0/\lambda$ , for ring-core and ring-ring structures (a). Deceleration  $N$  dependence on wavelength  $\lambda$  for usual loop SWS and for the same structure with a magnetic coupling (b).



## Slow-Wave Structures

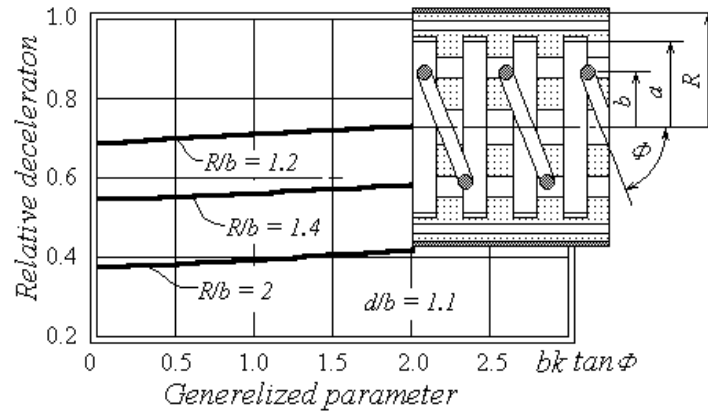
As it was shown in [12], the output power of helix TWTs is restricted by the maximum voltage (10kV). We offered and investigated many new SWS which could replace the common helix in high power devices. Some of them are shown below.

To increase a TWT output power, one should decrease a deceleration decreasing simultaneously the periodicity of the SWS. This means that the distance between neighbor conductors of the SWS in the longitudinal direction can't be equal or exceed a half of the slowed wavelength.

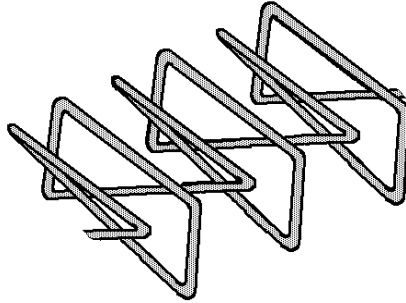
The longitudinal periodicity decreases twice in the case of a modified helix ("ring-core" in a practical application). Much more decreasing can be achieved by replacing the bars by declined rings (Fig. 7a).

The periodicity can be very small if the SWS is formed by a row of loops installed on a metal base. A very high dispersion is a disadvantage of such structure. The positive magnetic coupling between the neighbor loops decreases dispersion significantly (Fig. 7b).

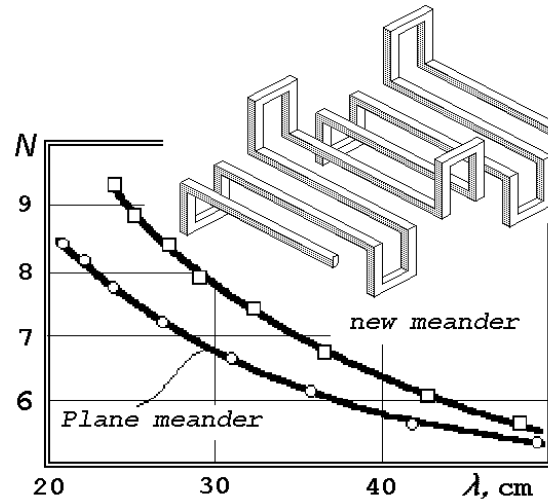
Omitting some interesting designs, we'll return to the current exited in the circumferential direction of the shell surrounding the helix. While the longitudinal conductance of the shell increases the deceleration and decreases the interaction factor, the azimuth conductance, vice versa, decreases the deceleration and increases the interaction factor. It follows from this that the row of conducting rings outside a helix (Fig. 8) may kill two birds: to obtain a relatively small deceleration in the helix with a small pitch (with a small periodicity) and to increase the interaction factor. It's interesting that such rings with capacitive gap can be used for a dispersion control [13].



**FIGURE 8.** Relative deceleration in the case of a helix in the combined shell for different ratios  $R/b$ .



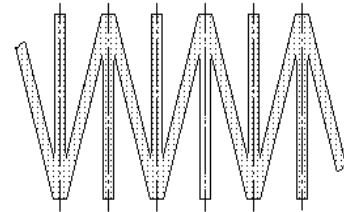
**FIGURE 9.** Rectangular helix with triangle winds.



**FIGURE 10.** Deceleration  $N$  dependence on wavelength  $\lambda$  for plane and bent meanders.

Rectangular helices are used sometimes in M-type devices. In this application, only one surface of the helix can be used for interaction with an electron beam that decreases the interaction factor. A helix, which winds have a triangle cross-section turned of at opposite directions one to another (Fig. 9), has higher interaction factor.

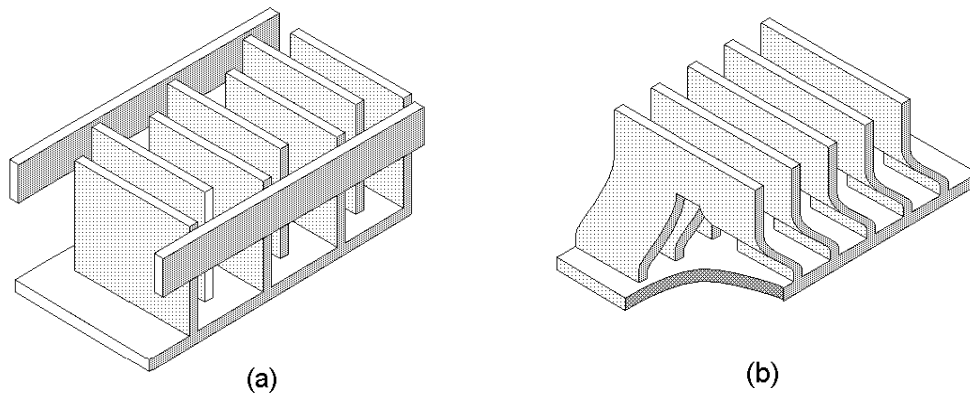
High periodicity and high slope of dispersion characteristic have such structures as meander- and zigzag-lines, sometimes called plane spirals. The dispersion of a meander-line can be improved by bending its edges (Fig. 10). Perpendicular strips in the zigzag-line (Fig. 11) also decrease dispersion.



**FIGURE 11.** Zigzag-line with perpendicular strips.

It should be noted that the coupled SWSs, such as shifted at half period in the longitudinal direction meanders or placed in parallel comb-type structures [14] have the relatively small deceleration dependence on frequency. The strong transverse electric field in such structures makes them to be useful for M-type TWTs.

Another rectangular structures, such as combs, have some very important advantages in comparison to a helix. A wide interaction zone of the comb and a large interaction factor together with a good heatproof make the comb to be indispensable for TWTs operating at millimeter and sub-millimeter wave bands. In the same time, a strong dispersion is its disadvantage. Using frequency dependent electric or magnetic coupling between ribs of the comb allows to decrease dispersion. In the first case (fig. 12a), two longitudinal plates provide capacitive coupling between even ribs and between odd ribs. Maximum electric coupling at  $\pi/4$  phase shift between neighbor ribs drops at  $\pi/2$  shift. In the second case, the magnetic field at the base of one rib interacts with magnetic fields of the neighbor ribs (Fig. 12b).



**FIGURE 12.** Comb structure with capacitive coupling (a) and inductive coupling (b).

It should be noted that many various slow-wave structures were examined to the present time. It was found that SWSs may be useful not only for wave interaction with electron beams but also for interaction with different mediums in numerous applications, such as electromagnetic heating, physiotherapy, measurements, etc, [15]. Such unconventional application of SWS can be a subject of the paper, comprising much more innovations than was presented above.

## CONCLUSION

It is not possible to show in a short paper all innovations in TWTs' theory and design, which were made by Loshakov's team during the 1950s-1970s. Only a small part of those achievements was considered above. The author had no possibility to present all references concerning the innovations exposed in this paper. Some of them are classified; listing of the others will take many pages.

## ACKNOWLEDGMENTS

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